USAARL Report No. 2018-12

Computerized Dynamic Posturography and the U.S. Army Rotary Wing Aviator: A Normative Study

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United States Army Aeromedical Research Laboratory

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May 2018

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
15-05-2018	Final	10-2015 - 12-2017

4. TITLE AND SUBTITLE	
Computerized Dynamic Posturography and the U.S. Army Rotary Wing Aviator: A Normative Study	5a. CONTRACT NUMBER N/A
	5b. GRANT NUMBER N/A
	5c. PROGRAM ELEMENT NUMBER N/A
6. AUTHOR(S) Karch, Stephanie J.; Milam, Lana S.; Staton, Robert N.	5d. PROJECT NUMBER S15
	5e. TASK NUMBER N/A
	5f. WORK UNIT NUMBER N/A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
U.S. Army Aeromedical Research Laboratory P.O. Box 620577 Fort Rucker, AL 36362	USAARL 2018-12
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army Medical Research and Materiel Command 810 Schreider Street Fort Detrick, MD 21702	USAMRMC
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) N/A

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

Laulima Government Solutions, LLC

14. ABSTRACT

Computerized dynamic posturography (CDP) interprets how the human body integrates vestibular, visual, and somatosensory inputs with neuromuscular systems to maintain balance. Normative CDP values utilizing clinically normal young adults are likely not representative of function for high-performing military personnel, and therefore may provide a limitation to the practicing clinician. An aviator military-specific normative database could then assist in return to duty (RTD) determinations for aviators who are recovering from either an injury to the vestibular, visual, or somatosensory systems that would affect postural sway and/or control. The goal of the current study was to define normal functional values for the tests of the CDP in military trained aviators. This includes the sensory organization test (SOT), head shake SOT, motor control test, and adaptation test. Forty-four military trained aviators completed the informed consent process and participated in the CDP portion of this study. Participants completed all tests of CDP, with test order pseudo-randomized in accordance with equipment limitations.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Loraine St. Onge, PhD
					19b. TELEPHONE NUMBER *(Include area code)*
UNCLAS	UNCLAS	UNCLAS	SAR	28	334-255-6906

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Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

14. Abstract (continued)
Results of this study suggest that military aviators are high performers when compared to the publically available aged matched normative values. These normative values may provide the practicing clinician guidance when interpreting the various tests of postural control in military aviators.

Acknowledgements

The authors would like to thank the following people for their contributions to this project:

- Dr. Ben Lawson for his guidance and foresight in study design.
- SGT Cierrah Azcona and Mr. Christopher Latin, Jr. for their assistance with both data collection and data entry.

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Introduction

Computerized dynamic posturography (CDP) interprets how the human body integrates vestibular, visual and somatosensory inputs with neuromuscular systems to maintain balance (Black, 2001; Shepard & Janky, 2008). A comprehensive CDP evaluation is a battery of three to four tests. The three standard subtests of the CDP are the Sensory Organization Test (SOT), the Motor Control Test (MCT), and the Adaptation Test (ADT). A fourth subtest, the Head Shake Sensory Organization Test (HS-SOT), is an enhancement of the SOT as the level of difficulty is increased compared to the SOT. While the CDP is complementary to tests of the vestibulo-ocular reflex like that of rotational chair assessments or caloric irrigation, it has poor sensitivity for dysfunction of the peripheral vestibular system (Black, 2001; Cripps, Livingston, & Desantis, 2016).

The SOT is the most widely used CDP test and is considered the gold standard test of postural control (Shepard & Janky, 2010). It is a functional test (not a site of lesion test) of how the body integrates sensory cues to maintain postural stability when the visual and/or somatosensory inputs are conflicted and when the head is static (Shepard & Janky, 2010). This is accomplished by systematically assessing the sensory inputs over six conditions, increasing in difficulty from condition (C) 1 to 6 (see Table 1). The MCT measures the body's automatic reaction to quick and unexpected forward and backward movements (Natus, 2013; Shepard & Janky, 2010). The ADT measures the individual's ability to adapt, habituate (i.e., develop and maintain a strategy) and maintain postural stability, to sudden, repeated unexpected changes. Although the ADT and MCT are similar, the movements in the ADT are vertical tilts (i.e., toes up or toes down conditions) as opposed to forward and backward translations (Natus, 2013).

Table 1. Sensory Organization Testing

	Eyes	Surface	Surround	Primary Sensory Cue
C1	Open	Fixed	Fixed	Somatosensory
C2	Closed	Fixed	Fixed	Somatosensory
C3	Open	Fixed	Sway-Referenced (Sway-Ref)	Somatosensory
C4	Open	Sway-Ref	Fixed	Vision
C5	Closed	Sway-Ref	Fixed	Vestibular
C6	Open	Sway-Ref	Sway-Ref	Vestibular

Note. Adapted from the Natus Medical Incorporated's Balance Manager Systems Clinical Interpretations Guide (2013).

The HS-SOT is an extension of conditions two and five of the SOT. It is ideal for patients whose SOT results are normal but still complain of instability and difficulty maintaining balance when walking or standing while the head is in motion (Shepard & Janky, 2010). The HS-SOT provides information regarding unilateral vestibular deficits by measuring postural stability during dynamic head rotations in the pitch (vertical), yaw (horizontal), or roll (shoulder to shoulder) plane(s) (Black, 2001).

A comprehensive CDP evaluation is typically warranted when a patients complains of either: 1) unsteadiness/imbalance while walking or standing without vertigo; and/or 2) frequent falls without injury. A comprehensive CDP evaluation can determine the functional effect of vertigo, ataxia, unilateral or bilateral vestibular hypofunction, pathologic involvement of the pyramidal/extrapyramidal or spinal tracts has postural control (Black, 2001; Shepard & Hanky, 2008, 2010).

A few studies have utilized CDP subsets with not only military Service Members (SMs) but with aviators. Baylor, McGrath, Molstad, Rupert, and Guedry (1992) utilized the SOT and found the balance function of military aviators to be significantly higher than the available clinical norms developed using a general non-pilot population. The authors also recommended the development of aviator-specific population norms for balance function.

Numerous operational and/or occupational environments like those in which military aviators find themselves have shown to have a negative effect on postural stability. Decrements in postural control among military pilots who completed simulated flight training was first noted by Kennedy, Fowlkes, and Lilienthal (1993). Additionally, Nordahl, Aasen, Owe, and Molvaer (1998) found acute hypobaric hypoxia experienced as low as 8,000 feet (ft), possibly increasing anterior/posterior sway and reducing postural control despite no complaints of dizziness or unsteadiness. Wagner, Saunders, Robertson, and Davis (2016) noted statistically significantly lower SOT composite scores at a simulated acute normobaric hypoxic altitude of 16,405 ft. Conversely, the MCT is said to not be affected by hypoxic state (Wagner et al., 2016). And finally, Sausen et al. (2003) reported that hypoxia can degrade not only sensory-motor function but situational awareness.

Common injuries in the military aviation population that also degrade postural control and reaction time to unexpected perturbations include: mild traumatic brain injuries (mTBI), back pain, neck injuries (e.g., whiplash), spinal injuries, and lesions along the long-tracts of the musculoskeletal system (Kelley, MacDonnell, Girgley, Campbell, & Gaydos, 2017; Kogler, Lindfors, Odkvist, & Ledin, 2000; Lawson & Rupert, 2010; Shepard & Janky, 2008). These injuries can occur during occupational tasks, recreational activities, or activities of daily living.

Utilizing the subtests of a CDP evaluation can provide a “snapshot” of functional balance at the time of evaluation. A comprehensive CDP evaluation can also be used to identify those patients who may benefit from vestibular rehabilitation therapy, and to track recovery (i.e., return to duty, [RTD]) after neurosensory injuries (i.e., concussion or traumatic brain injury). Currently, limited published information is available regarding military fitness for duty (FFD), RTD and CDP evaluations. The SOT has already been reported as an acceptable in-theater assessment to determine RTD after a mild traumatic brain injury (mTBI) (Haran et al., 2016). Published findings in the arena of sports medicine (i.e., recent emphasis on return to play after an on field concussion) often influence RTD after a neurosensory injury (Haran et al., 2016; Scherer, Weightman, Radomski, Davidson, & McCulloh, 2013; Schmidt, Register-Mihalik, Mihalik, Kerr, & Guskiewicz, 2012).

As cited in Roma (2005), Clark, McGrath, Anderson, Shortal and Rupert (1998) report the use of the HS-SOT in U.S. Naval aviation candidates. The original authors found that the equilibrium score (ES) of the HS-SOT was able to discern significant differences in vestibular function after exposure to a stressful flight simulation. The same cohort under the same experimental conditions with postural control measured with the SOT revealed no significant difference noted via equilibrium scores (ESs) pre- versus post-flight simulation. This would suggest that the HS-SOT does indeed measure a unique aspect of vestibular function in the maintenance of postural stability. Further information and original publication was not accessible via public literature searches, and therefore cannot be further discussed at this time.

The use of individualized baselines for performance on tests of balance function may be logistically challenging for the practicing clinician to say the least. Schmidt et al. (2012) suggested the use of a normative database for the SOT may be useful and appropriate in post-injury evaluations. This was determined after comparing post-concussion scores for collegiate athletes to both the individual's baseline value (i.e., before injury) and to the normative mean.

Normative values created utilizing general population controls are likely not representative of functional balance for high-performing military personnel, which may provide a limitation to the practicing clinician (Baylor et al., 1992; Paloski, Reschke, Black, & Dow, 1992; Pletcher et al., 2017). Thus, direct application of non-military functional balance normative data is cautioned due to Service Members (SMs) experiencing stressors (e.g., sleep deprivation, fatigue, dehydration, stress) that are known to influence postural control at a level not often found in non-military populations (Haran et al., 2016; Scherer et al., 2013). Consequently, normative data in healthy, asymptomatic, military personnel specific to occupational series may prove to be useful for both RTD and FFD determinations. Similarly, Gotshall and Hoffer (2010) recommended that vestibular clinics establish and utilize military-specific normative data. Despite the recommendation of the development of military-specific normative values, limited published databases are available.

The goal of the current study was to define normal functional values for CDP tests in military-trained aviators (i.e., pilots and flight students). A normative database of balance function could be developed from the normal functional values defined in this study and could be used in RTD determinations for aviators who are recovering from either an injury to the vestibular, visual, or somatosensory systems that would affect postural sway and/or control.

Methods and Materials

The goal of the current study was to create a normative database for each test of the CDP utilizing the results of at least 40 U.S. military-trained aviators (Active Duty, Reserve, and National Guard). As seen in Table 2, the consented, screened, and enrolled participant sample size varied by test. This is due to the exclusion of data from: a participant who was disqualified (n = 1), invalid MCT results due to a measured latency of 0 (n = 2), and high-head velocity with low equilibrium ratio score on the HS-SOT (n = 3).

Table 2. Number of Participants Included for Analysis

Consented	Screened	Enrolled	SOT	HS-SOT	MCT	ADT
44	44	44	43	40	41	43

Participants

A total of 43 (41 male; 2 female) military-trained aviators (Active Duty, Reserve and National Guard) aged 23 to 40 years (32.2 $\pm$ 4.0) and between 61 to 78 inches in height (70.1 $\pm$ 3.1) completed all four CDP tests. All participants were SMs (rated rotary-wing pilots or flight students) who held medical clearance for flight operations and had no reported history of vestibular or balance disorders or oculomotor difficulties. Possible participants were informed of exclusion/inclusion criteria prior to enrollment allowing for self-exclusion without collecting any data. To ensure participants met inclusion criteria (Figure 1), participants were screened with two questionnaires. However, the questionnaires were not specific to the exclusion criteria. The first was a protocol-specific demographic questionnaire, which asked questions such as, but not limited to: birth year, height, total flight-hours, aircraft rated to fly, medication use. The second questionnaire participants completed was the Dizziness Handicap Inventory (DHI) (Jacobson & Newman, 1990). The average DHI score for all participants was zero. All participants provided informed consent prior to any data collection.

- Does not have current medical clearance to fly
- Recent history of dizziness or lightheadedness (more than one episode in the past month)
- Recent "whiplash" or other serious neck injury within the last 5 years or not fully recovered
- Lower limb injury or surgery within the last six months
- History of two or more unexplained falls within the past 6 months
- History of head injury (e.g., TBI) or concussion with reported symptoms in the past six months
- History of exposure to high-level blast within the last 5 years or not fully recovered
- Diabetes
- Self-reported confirmed or possible pregnancy
- Prior disorders of hearing and balance including:
    - Ménière's disease
    - Chronic Migraine headaches
    - Multiple Sclerosis
    - Vestibular neuritis
    - Vestibular schwannoma
    - Sudden sensorineural hearing loss
    - Major cerebrovascular disorders
    - Systemic disorders: chronic renal failure, cirrhosis of the liver, etc.

Figure 1. Study exclusion criteria.

Equipment

The NeuroCom SMART EquiTest® Clinical Research System* (CRS) (Natus Medical International, Clackamas, OR) with the Data Acquisition Toolkit (version 9.3) was used. The Equitest® CRS utilizes an 18" x 18" dual force plate and visual surround. The force plate and the

* See manufacturer's list.

visual surround can move in relation to the participants' anterior-posterior sway. Pitch rotation of both the force plate and visual surround is controlled by independent direct servo motors. Additionally, the force plate can translate forwards and backwards or rotate up and down ± 10 degrees (deg) and speed (maximum velocity of 50 deg/sec) based on the protocol design. The HS-SOT required the additional use of a head tracker (three-axis sensor and accelerometer) to monitor head location and head-shake velocity.

Procedure

The procedure presented herein is a subset of the Institutional Review Board (IRB) approved protocol. Dynamic vision results (i.e., Perception Time Test, Stative Visual Acuity, Dynamic Visual Acuity and Gaze Stabilization) are reported elsewhere. The CDP tests completed were the Sensory Organization Test (SOT), Head Shake SOT (HS-SOT), Motor Control Test (MCT), and Adaptation Test (ADT). Test order (e.g., CDP first, gaze control second) was counterbalanced by participant study number. Within the CDP test block, the test order was pseudo-randomized, as complete randomization was not possible due to equipment limitations. The equipment protocol requires SOT C2 and C5 to be completed prior to the HS-SOT. To eliminate complications or redundancy, the SOT consistently preceded the HS-SOT.

Once both screening questionnaires (demographic and DHI) were complete and prior to stepping upon the platform, all participants were asked to remove their footwear and don a pair of non-slip socks and a safety harness. The safety harness was then attached to the safety bar and straps on the platform to mitigate fall risks. The participant was assisted up and onto the platform, ensuring proper foot placement. Participants were provided instructions prior the commencement of each test.

Sensory Organization Test (SOT)

Participants completed at least three trials of each condition (see Table 1). Each trial was 20 seconds in length. Instructions given to each participant were to look forward, maintain a quiet and natural stance with arms by his or her side, avoiding locking his or her knees while keeping both feet in the pre-designated location throughout testing. Only in C2 and C5 were participants asked to close their eyes prior to the start of testing. If a participant lost balance or touched the wall, the trial was marked a fall and not included in analysis (Natus, 2013). Outcome measures of the SOT include the ES for each of the six conditions, a total composite score (COMP), and four sensory organization ratios (i.e., somatosensory [SOM], visual [VIS], vestibular [VEST], and preference [PREF]). The ES for each condition is an average of the three trials for said condition, while the composite score is a weighted average of all six individual ES. Scores are based on the individual's maximum anterior-posterior sway (deg) compared to the theoretical allowable sway (12.5 deg) and expressed as a percentage from 0 to 100. Larger equilibrium scores (ESs) (i.e., near 100%) suggest a greater sense of stability.

The sensory analysis ratio (SOM, VEST, and VIS) determine an individual's ability to use input from the respective sensory cue to balance stability. The visual preference ratio (PREF) refers to the degree to which the individual is reliant upon visual information in the maintenance of balance, despite it providing inaccurate information (see Table 3) (Natus, 2013). All outcome measures were automatically calculated and scored by the data acquisition software. The interested reader is encouraged to review Natus' Clinical interpretations Guide (2013) for further detail on the development and interpretation of all test results.

Table 3. Sensory Organization Test – Sensory Analysis Ratio

Sensory Ratio	Ratio	Sensory Cue Evaluated
Somatosensory (SOM)	$\frac{C2}{C1}$	Somatosensory
Visual (VIS)	$\frac{C4}{C1}$	Visual
Vestibular (VEST)	$\frac{C5}{C1}$	Vestibular
Visual Preference (PREF)	$\frac{(C3+C6)}{(C2+C5)}$	Visual reliance, even if inaccurate

Note. Adapted from Nashner (1997); Natus (2013).

Head Shake Sensory Organization Test (HS-SOT)

The HS-SOT was completed immediately after the SOT subtest. The participant was asked to complete six 20-second trials for both test conditions (see Table 4) with a minimum peak head velocity of 85 deg/sec. Only data obtained in trials two to six for both test conditions are to be included in data analysis (i.e., trial one is recorded, as a practice and then discarded). Participants were given the same instructions as during C2 and C5 of the SOT. However, they were required to don the head tracker and asked to turn their head continually back and forth without stopping (20-deg to the right and left). Prior to data collection initiation, participants were allowed to practice the desired range and velocity of head movement. If the participant touched the walls or fell, data from that trial was not included and the trial was immediately repeated. Once the HS-SOT was complete, the head tracker was removed.

The HS-SOT provides an ES (0 to 100%) similar to that of the SOT for each test condition trial. In addition, head shake velocity were also reported. The outcome measure of choice for this study was the overall ES ratio. The ES ratio compares the ES under static (i.e., SOT C2 and C5) and dynamic (i.e., HS-SOT C2 and C5) conditions.

Table 4. Head Shake Sensory Organization Testing

	Eyes	Surface	Surround	Head Movement	Sensory Cues
C2	Closed	Fixed	Fixed	Yaw; 85 deg/sec	Vestibular, Somatosensory
C5	Closed	Sway-Ref	Fixed	Yaw; 85 deg/sec	Vestibular, Somatosensory

Note. Adapted from the Natus's Clinical Operation Guide (2013).

Motor Control Test (MCT)

Participants were to maintain postural control while looking forward with a quiet and natural stance (i.e., arms by their side with knees not locked). The platform moved forwards (i.e., anteriorly) in small, medium, and large translations (three trials in each magnitude size). This same procedure (i.e., three trials in each of the three magnitude sizes) was then repeated with the platform moving backwards or posteriorly. The distance in which the platform moved was normalized to the participant's height. This allowed all test results to be included in the analysis without concern for height. If the participant touched the walls, turned around or fell, data from that trial was not included and the trial was immediately repeated.

The outcome measure of interest was motor response latency as measured in milliseconds (ms). The response latency is the time delay between the onset of the platform translation and the recorded corrective response (Nashner, 1997; Shepard & Janky, 2008) and is measured automatically by the data acquisition software. The data acquisition software utilizes four algorithms to automatically score and measure the response latency. Depending on the number of algorithms in agreement, each score is assigned a rating of 0 (no agreement) to 4 (full agreement). If latency values were greater than 200 ms and/or if the agreement rating was less than or equal to two, the latency was manually inspected to ensure accurate results for analysis.

In accordance with Natus' normative approach, latency normative values will be established for medium and large translations only. The short translations are considered "practice" and not included. Test measures such as weight symmetry, strength symmetry and response strength (i.e., amplitude scaling) were also not included for analysis.

Adaptation Test (ADT)

Participants completed five trials of the toes up and toes down conditions. Each trial is an 8-deg rotation completed in 400 ms. Instructions given to each participant was to look straight ahead with their eyes open and to maintain postural control throughout testing. Participants were instructed to stand quietly in a natural stance with their arms by their side, avoid locking their knees, and keep both feet in the pre-designated location throughout testing. If a participant stumbled, touched the wall, or fell, the trial was marked as a fall and not included in the analysis.

The outcome measure for the ADT is the sway energy score. The sway energy score measures the magnitude of the participant's force response required to overcome the induced instability. This was calculated for each trial within the condition.

Statistical Analysis

Descriptive statistics were used to describe performance on each test of CDP. That is, the mean (M), standard deviation (SD), median (Mdn), and interquartile range (IQR) for each test was analyzed for general trends. As described by Nashner (1997) and again in Natus' Clinical Operations Guideline (2013), the NeuroCom® database utilizes the 5th percentile as the normal cutoff value. Study normative values were developed utilizing this approach. SOT normative values were developed utilizing the 5th percentile (i.e., M – 1.67 SD) for C1 through C6 equilibrium score (ES), the overall comprehensive (COMP) score, and all four sensory analysis ratio values (i.e., SOM, VIS, VEST, PREF). Conversely, the cutoff normative values for MCT latency, and ADT sway energy scores were developed using 1.67 SD above the mean (i.e., M + 1.67 SD). The NeuroCom® normative database does not include values for the HS-SOT at this time. As a significant decrease in stability would be of concern and considered abnormal, utilizing the 5th percentile score (i.e., M – 1.67 SD) as a cutoff would be valuable. Study normative values were then compared to NeuroCom's® normative values of adults (non-aviator) aged 20 – 59 (Nashner, 1997; Natus, 2013). IBM® SPSS® Statistics version 23 was used for all analyses (Armonk, NY).

Results

SOT

Forty-three participants completed a minimum of three trials of all six-test conditions. Descriptive statistics (i.e., M, SD, Mdn, and IQR) for ESs for conditions one to six (C1 to C6), the total comprehensive score, and the four sensory analysis ratios are provided in Table 5. Developed normative values (M – 1.67SD) using study means and standard deviations are provided in Table 6. Comparison to non-aviator data is also provided and adapted from Natus (2013) and Nashner (1997).

Table 5. Sensory Organization Test Descriptive Statistics

	EQL Score						
	C1	C2	C3	C4	C5	C6	COMP
M	94.3	91.9	91.8	87.5	72.7	74.6	83.2
SD	1.7	1.9	1.9	5.5	6.8	9.1	3.7
Mdn	94	92	92	88	73	75	83
IQR	94-95	91-94	91-93	85-91	69-77	68-81	81-86

	Sensory Ratio			
	SOM	VIS	VEST	PREF
M	97.7	92.9	76.7	101.5
SD	2.1	5.5	6.3	5.2
Mdn	98	94	77	102
IQR	96-99	90-97	72-81	100-105

Table 6. Sensory Organization Test Normative Values.

	C1	C2	C3	C4	C5	C6	COMP	SOM	VIS	VEST	PREF
Aviator	91	89	89	78	61	59	77	94	84	66	93
Non-Aviator	90	85	86	70	52	48	70	90	74	55	86

Note. Scores developed using 5th percentile scores (M – 1.67 SD).

HS-SOT

The data of 40 participants was included for analysis. Equilibrium scores reflect the average of trials two through six (trial one was practice and not included in analysis). The equilibrium ratio reflects the ratio of performance for static (i.e., SOT C2, SOT C5) and dynamic conditions (i.e., HS-SOT C2, HS-SOT C5). Descriptive statistics for all participants is provided in Table 7. Table 8 includes the developed normative values utilizing a cutoff of 1.67 SD below the mean.

Table 7. Head Shake – Sensory Organization Test Descriptive Statistics

	EQL Score		EQL Ratio	
	Fixed	Sway-Ref	Fixed	Sway-Ref
M	90.5	59.5	0.99	0.82
SD	3.0	10.2	0.03	0.11
Mdn	91	62	0.98	0.82
IQR	89-92	52-65	0.97-1.00	0.74-0.90

Table 8. Head Shake – Sensory Organization Test Normative Values

EQL Score		EQL Ratio	
Fixed	Sway-Ref	Fixed	Sway-Ref
86	42	0.94	0.64

Note. Scores developed using 5th percentile scores (M – 1.67 SD).

MCT

The data from 41 participants was included in data analysis. Descriptive statistics (Table 9) were calculated for the motor response latency for all possible magnitude and surface translations measured at the right and left feet. The study developed normative values (M + 1.67 SD) for latency compared to available normative data (Natus, 2013) is provided in Table 10. Following suite with Natus (2013), normative values were not calculated for the small translations (neither backwards nor forwards).

Table 9. Motor Control Test – Latency Descriptive Statistics

	Backward Translation					
	Sm L	Sm R	Med L	Med R	Lrg L	Lrg R
M	144.4	144.9	135.6	132.4	128.5	126.3
SD	16.4	11.2	9.8	11.1	9.9	9.1
Mdn	140	140	140	130	130	130
IQR	135-160	140-150	130-140	130-140	120-135	120-130

	Forward Translation						COMP
	Sm L	Sm R	Med L	Med R	Lrg L	Lrg R	
M	150.2	151.2	145.9	140.2	138.8	134.6	135.3
SD	23.1	21.5	10.7	9.6	11.4	8.4	6.6
Mdn	150	150	150	140	140	130	138
IQR	140-160	140-155	140-150	130-150	130-150	130-140	130-140

Note. Unit of measure is ms.

Table 10. Motor Control Test – Latency Normative Values

	Backward Translation				Forward Translation				COMP
	Med L	Med R	Lrg L	Lrg R	Med L	Med R	Lrg L	Lrg R	
Aviator	152	151	145	141	164	156	158	149	146
Non-Aviator	150	150	140	140	160	160	160	160	157

Note. Unit of measure is ms. Equation used for calculating normative values is M + 1.67 SD.

ADT

The data from all 43 participants was included for data analysis. Table 1 indicates descriptive statistics for the sway energy scores in the toes up (TU) and toes down (TD) conditions. Developed study normative values compared to an adult (non-aviator) population is in Table 12. Non-aviator data is adapted from Natus (2013) and Nashner (1997).

Table 11. Adaptation Test – Sway Energy Descriptive Statistics

	TU1	TU2	TU3	TU4	TU5	TD1	TD2	TD3	TD4	TD5
M	69.3	53.6	51.2	46.4	46.8	38.5	33.5	32.8	31.5	31.5
SD	15.0	11.0	8.7	7.4	8.3	6.7	7.5	7.2	6.8	6.5
Mdn	68	52	51	45	45	37	32	31	31	31
IQR	59-79	45-59	43-56	41-53	42-51	34-42	28-38	28-37	26-34	27-36

Table 12. Adaptation Test – Sway Energy Normative Values

	TU1	TU2	TU3	TU4	TU5	TD1	TD2	TD3	TD4	TD5
Aviator	94	72	66	59	61	50	46	45	43	42
Non-Aviator	160	109	99	76	75	133	66	58	54	50

Note. Normative values were developed utilizing the equation M + 1.67 SD.

Discussion

This study provides a normative database for the tests of CDP, which includes the SOT, HS-SOT, MCT, and the ADT. The normative values were developed utilizing the test results from a cohort of U.S. military pilots and flight students who met the following criteria: 1) denied prior history of vestibular, oculomotor, or balance related problems; and 2) held a current medical clearance for flight activities. While published normative databases for postural control within the U.S. military is limited (Pletcher et al., 2017), there are a number of studies published regarding subclinical populations (e.g., migraine, mTBI) in the U.S. military (Cho, Clark, & Rupert, 1995; Hoffer et al., 2010) using the SOT. It is to the best of our knowledge that this is the first instance of a comprehensive database of normative CDP values specific to U.S. military aviators.

The developed database was created utilizing performance values from a clinically normal population of military trained aviators. Therefore, the reported test values can used by clinicians and military service providers whose patients are pilots, flight students, and/or other high-performing military clinical population in the evaluation of postural control. Additionally, these results may be of interest to a clinician or service provider required to make determinations regarding: RTD, FFD, post-TBI, and/or vestibular dysfunction, and other duty-related status determinations.

Noted limitations in this study are that participants may not have disclosed a history of injuries (like that of a traumatic brain injury or blast exposure) that have a strong likelihood of affecting the vestibular and/or balance system (Gottshall, 2011; Gottshall & Hoffer, 2010; Scherer, Burrows, Pinto, Littlefield, French, Tarbett, & Schubert, 2011). Participants were excluded if they reported current symptoms of TBI or blast exposure, and were required to have a current military medical clearance for flight. As this study was not a hypothesis-driven study, a control cohort (i.e., military non-aviator) population was not assessed. Therefore, no comment can be made regarding difference in postural control between military aviators and military non-aviators.

In a study of fixed-wing fighter pilots, Aschan (1954) suggested that the vestibular response of an aviator reverts to that of a non-aviator in the "absence of flying for a long period (months)" (p. 31), with no specific time frame given. Participants were asked the total number of flight hours they had accrued up to the date of administration of the informed consent. However, they were not asked the amount of time between their last flight and participation in this study. A search of the literature revealed no further information regarding the amount of time in which this regression occurs, or a replicative study to concur with Aschan's findings. The current study only evaluated pilots on active flight status; thus, no comparison can be made with Aschan's findings.

SOT

The SOT results revealed average ESs and analysis ratios higher than that of NeuroCom®'s developed normative values for 20 to 59 year olds (seen in NeuroCom®'s Clinical Interpretations Guide, Appendix A, 2013). This is true for all conditional tasks (C1 to C6), the composite score, and all sensory analysis ratios (SOM, VIS, VEST and PREF). Other studies of young adults within the same age range (23 to 40) who are clinically normal populations like that of Borah et al. (2007) show mean ESs below the study means on C1, C3, C4, C5, C6, and the COMP. When comparing our results to the published mean ESs of Nashner (1997), the more challenging conditions (C3 to C6) resulted in higher equilibrium means (i.e., greater stability) within the military aviator population. These findings would suggest less sway (i.e., mean equilibrium) is present in a cohort of military aviators than in a clinically normal general population. This further suggests that military aviators should not be compared to clinical norms developed from the general population.

When comparing the current study values to populations of high performers, like that of collegiate athletes, we find similar performance values. Broglio, Macciocchi, and Ferrara (2007) reported the baseline SOT values of 75 Division I collegiate athletes (age range was not provided). The reported COMP score was 82.4, while our mean was a similar 83.2. Both scores are well above the 79.8 mean score for 20 to 59 year olds (Natus, 2013). Additionally, Broglio et al. (2007) baseline SOM, VIS, and VEST sensory analysis ratios were 96.4, 93.4, and 76.9, respectively. This closely mirrors our own mean scores of 97.7 (SOM), 92.9 (VIS), and 76.7 (VEST). Higher than equipment normative values were also reported in a cohort of collegiate athletes (Division I and intramural) on the COMP score, the VIS, VEST, and SOM sensory analysis ratios, days following a known concussive event (Guskiewicz, Riemann, Perrin, & Nashner, 1997).

Results from the current study closely mirror the reported SOT means (C1 to C6, COMP score, and sensory ratios) in a population of Active Duty U.S. Special Force Operators (Pletcher et al., 2017). Noted variance between cohorts may be due to sample size, as the Pletcher et al. (2017) study is considerably larger with an *N* of 545. A control cohort of Active Duty U.S. Navy SMs was referenced in a study by Hoffer et al. (2003). However, the normative values were not published resulting in the inability for a cohort comparison.

Baylor et al. (1992) noted that U.S. military aviators had functional balance scores well above the normal clinical data previously established by a population of non-aviators. As cited by Cho et al. (1995), the Baylor et al. (1992) data reported mean scores of 94 for C2 and 73 for C5 in a cohort of U.S. Naval aviators. Our mean ESs in these two conditions were 92 (C2) and 73 (C5). This noted variance between aviator cohorts may be due to a number of factors – sample size differences, inclusion/exclusion criteria, occupational series, and so on. Further study values for the remaining conditions and sensory analysis scores were not available for comparison to the current cohort.

Normative values for Spanish soldiers was published in a study examining the effect that spatial disorientation has on postural stability in a population of Spanish Air Force fighter and transport pilots (Lorente, Esteban, Vallejo, Rios, & Garcia-Alcon, 2002). The ESs for C1 to C6 and sensory analysis ratios for the control group in the Lorente et al.'s (2002) study were higher than the results of our normative rotary-wing aviator trained population. This difference in score may again be due in part to sample size, as the Lorente et al. (2002) study control group (Spanish soldiers) had an *N* of 250 between the ages of 20 to 45, or other factors such as airframe.

The noted differences between military and non-military general population is apparent. The result from the current study are in agreement with results of similar high-performance military occupations (Baylor et al., 1992; Pletcher et al., 2017) and supports the notion that military specific normative values should be developed and applied. This would be particularly true for an occupational series that demand high performance.

HS-SOT

Noted published HS-SOT studies have various parameters, making generalization difficult to either the current or between published studies. Literature regarding the effect of head movement (i.e., head shake) on the maintenance of postural control among cohorts of both clinically normal young adults from either a general population (Honaker, Converse, & Shepard, 2009; Pang, Lam, Wong, Au, & Chow, 2011; Park et al., 2011; Peters, 2007) or high-performing population (e.g., aviators, astronauts, collegiate athletes, SMs) are limited (Cripps et al., 2016; Jain, Wood, Feiveson, Black & Paloski, 2010; Paloski et al., 2006). At this time, NeuroCom® does not employ normative values for this test. Rather, result interpretation is reliant upon the clinician's consideration of individual's performance, activities of daily living, and available normative values in the published literature.

Peters (2007) reports the difference in ESs between the HS-SOT and the SOT on similar conditions (e.g., SOT C2 versus HS-SOT C2) in normal individuals should be less than 30%. Utilizing this comparison, the difference between C2 mean scores of the SOT and HS-SOT for our study population was 1.5% on C2 and 13.4% on C5. This is well within the expected normal difference between stable and sway-ref support surface.

Although not a normative study, Park et al. (2011) characterized the performance of asymptomatic clinically normal adults on the HS-SOT. In their sample of young adults (aged 20 to 39), mean (SD) percent ES for C2 was found to be 91.38 (2.38) and 39.20 (10.77) for C5. Comparing these findings to our own, C2 scores are somewhat similar, varying by less than 1 point between the two study cohorts. However, a noted difference is present in the more challenging test of vestibular function, C5, with a difference between the two study cohorts of approximately 20 points. Park et al. (2011) also reported the equilibrium ratio for their young adult cohort to be 0.30 (0.03) for the sway-ref surface condition. In comparison, our aviator adult cohort had a mean (SD) sway-ref equilibrium ratio of 0.82 (0.11). These findings would suggest that the aviator cohort expressed a greater degree of postural control and stability in the same test condition in which the vestibular system is stimulated, than those of similar-aged adults from the general population.

Cripps et al. (2016) utilized similar test parameters (minimum velocity of 85 deg/sec, amplitude of 40 deg, and rotation in the horizontal plane) in their test-retest evaluation of 20 collegiate athletes (aged 18 to 24). Comparing our results with the Cripps et al. (2016) results found that the collegiate athlete demonstrated greater postural control than our aviator cohort. For the collegiate athlete cohort, the fixed surface ratio was 1.00 and the sway-ref ratio was 0.94, compared to our own ratios of 0.99 (fixed) and 0.82 (sway-ref). The noted difference in the sway-ref scores may be due to recorded head velocity (explained in more detail in the next paragraph), in addition to the sample size (20 compared to 40), and age range (the Cripps et al. population was considerably younger). Also collegiate athletes may have training that specifically improves postural control. For aviators, it is a by-product.

The mean equilibrium ratio results from the current study with a minimum peak head velocity of 85 deg/sec suggest participants showed an increase in postural sway in the unstable surface condition (i.e., HS-SOT C5) with a mean score of 0.82 and a developed normative cutoff of 0.64 (scores below this would be considered abnormal). As evidenced by a large SD (0.11), the range of scores on this subtest (HS-SOT C5) is 0.74 to 0.90. The fixed surface condition however has a recorded range of performance from 0.97 to 1.00 (M = 0.98). The introduction of an unstable surface (HS-SOT C5) removes the somatosensory cues available at the feet and ankles; therefore, a decrease in performance is expected. Though participants were instructed to maintain a minimum target velocity of 85 deg/sec, often the recorded velocity exceeded this value. When a high velocity was noted, participants were reinstructed to a more appropriate speed. It is likely that an increase in head velocity, beyond that of the minimum target, in the presence of an unstable surface can increase the individual sway despite normal vestibular function.

Flying, unlike typical bipedal terrestrial locomotion, includes dynamic movement in three dimensions. Therefore, evaluation of head movements in other planes of excitation is warranted. This is a noted limitation of the current test paradigm, as only head rotations in the horizontal (yaw) plane were examined.

MCT

The MCT latency response results revealed larger mean scores for both the medium and large backward translations, indicating a delayed reaction time than that of values provided by NeuroCom® for 20 to 59 year olds (NeuroCom® Clinical Interpretations Guide, Appendix A, 2013). Despite these differences, the developed normative value revealed a COMP score 9 ms less than general population values. This would suggest that the study cohort had an overall quicker reaction time than the aged matched adult norms. This may be due in part to quicker responses measured in the forward motion in the aviator cohort. Also, the sample size between cohort differed, with the current cohort twice as many data points (n = 41) than the non-aviator population (n = 20). Finally, looking at the variability in performance (i.e., SD) within the two cohorts, one notes that the non-aviator population had wide range in performance (large SD) in all but one condition (forward medium left).

Limited published results of a clinically normal population of young adults (i.e., less than 40 years of age) are available (Natus, 2013; Nashner, 1997). Nashner (1997) reports that the general trend amongst asymptomatic adults is a shorter measured response time in the large translations compared to the medium translations. Comparable results were found within the current study cohort.

According to Nashner (1997), one of the greatest likely errors in latency responses for the MCT is due to an unweighting of one leg during testing. This may explain a noted slight asymmetry between the measured average latencies between the right and left legs, particularly the medium forward and backward translations.

Despite numerous searches for MCT performance values and results among high performing cohorts (i.e., athletes, aviators, military SMs), only an abstract by Baylor et al. (1992) was found. Baylor et al. (1992) reported that MCT scores were calculated in their cohort of U.S. Naval aviators, however, the normative values were not available for comparison. The abstract did note however a significant gender difference, with males responding and correcting faster (i.e., reduced reaction time) than that of female aviator participants.

ADT

The ADT results from the current study revealed average energy sway scores (deg/sec) less than that of the NeuroCom® developed normative values for 20 to 59 year olds (NeuroCom® Clinical Interpretations Guide, Appendix A, 2013). This would suggest that the current study cohort expressed greater degree of postural control to unexpected rotations of the ankle and foot across all TU and TD conditions. Nashner (1997) indicated the anticipated trend of performance for clinically normal populations is a reduction in sway from the first to last condition in both the rotation conditions (up and down). This was found to be true in our study population. Like that of the MCT, published results of a clinically normal population of young adults (i.e., less than 40 years of age) is limited (Natus, 2013; Nashner, 1997).

Conclusions and Recommendations

The results of this study suggest that military pilots and flight students are high-performers when compared to the publically available aged-matched normative values (Natus Medical Incorporated, 2013). This is demonstrated with a higher measure of stability during the conditions and measures of the SOT and ADT, a faster response rate for unexpected forward translations with measures of the MCT.

Future research efforts should focus on further exploration and development of all CDP tests. Concerning the SOT, a comparative study of fixed-wing to rotary-wing pilots to determine if occupational and operational demands influence postural control is of continued interest. Additionally, an effort to determine the relationship between the SOT PREF (reliance on visual cues despite its inaccuracy) sensory analysis ratio and spatial disorientation susceptibility could be of particular interest to the aviation community. Future efforts utilizing the HS-SOT could include analyzing performance for a clinically normal sample population of military SMs and aviators under varying test paradigms (i.e., velocity rate and plane of excitation). Regarding all tests of the CDP, influence of age (i.e., aviators older than 40 years) and time since last flight on postural stability should also be explored.

The main objective of this study was to establish a normative database for the tests of the CDP (i.e., SOT, HS-SOT, MCT, ADT) utilizing a clinically normal population (i.e., asymptomatic) of military trained aviators. The results from this study will assist those medical service providers administering and/or interpreting any one of the previously mentioned tests, as the results from this study can serve as a comparison cohort either for patients who are military aviators or on aircrew status. These results may also assist in determining individual function for either RTD or FFD evaluation for either aviators and/or other high-performing military populations.

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